Collaborating Hearing Aids

An Information-Theoretic Perspective

Olivier Roy

LCAV - I&C - EPFL

Joint work with Martin Vetterli

May 15, 2007

Outline

Motivations (1/3)

Generalities

- Battery-operated sensing devices
- Types: behind-the-ear (BTE), in-the-ear (ITE), in-the-canal (ITC) and completely-in-the-canal (CTC)

- Analog vs. digital
- Few (omni-)directional microphones, 1 loudspeaker

Motivations (2/3)

Ultimate goal: improve speech intelligibility

- Spectral shaping
- Beamforming
- Assistive listening devices

(a) (b)

Figure: Assistive listening devices. (a) Remote microphone. (b) Collaborating hearing aids.

Motivations (3/3)

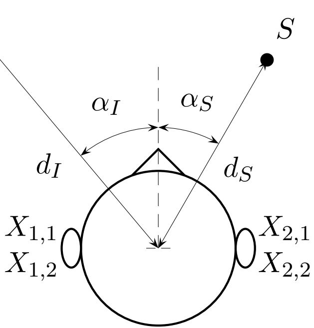
Wireless collaboration

- Analog vs. digital
- Transmission method (e.g. Bluetooth)
- Limited communication bitrate: coding issues

Gain-Rate Tradeoff

Collaborating Hearing Aids (1/3)

Recording setup

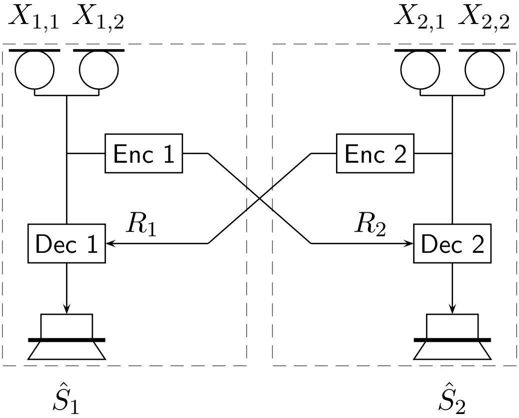


Recorded signals

$$X_{l,k}(t) = [h_{l,k} * S](t) + [g_{l,k} * I](t) + N_{l,k}(t), \quad \text{for } l,k = 1,2$$

Collaborating Hearing Aids (2/3)

Wireless collaboration scheme



Distortion criterion $d(S_k, \hat{S}_k)$ (e.g. MSE, perceptual, etc.)

Collaborating Hearing Aids (3/3)

Our ultimate goal: collaborative beamforming

- Theory
  - Information-theoretic framework
  - Combine signals recorded at both ears
  - Multi-channel Wiener filtering with rate constraints
  - Characterize the optimal gain-rate tradeoff
- Practice
  - Stringent constraints: power, delay, bitrate, synchronization
  - What do we keep from theory? What do we throw away?

Collaborative Beamforming: Theory (1/5)

Source coding in a nutshell

$$S \longrightarrow \boxed{\text{Enc}} \xrightarrow{R} \boxed{\text{Dec}} \longrightarrow \hat{S}$$

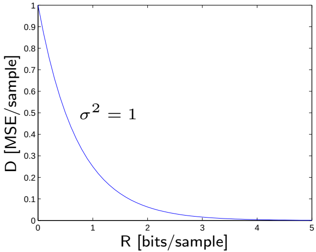
- Given: a source (or signal) S and a distortion criterion $d(S, \hat{S})$
- Question: for a given rate R, what is the minimum achievable distortion?
- Answer: the rate-distortion function
- Assumption: unbounded coding delay and complexity

Collaborative Beamforming: Theory (2/5)

Example: the Gaussian case

- We observe $X_1, X_2, \ldots$ where $X_k \sim \mathcal{N}(0, \sigma^2)$ i.i.d.
- Rate-distortion function given by

$$D(R) = \sigma^2 2^{-2R} \quad \text{[MSE/sample]}$$



- simple 1-bit quantization $\approx 0.36\sigma^2$, optimal $= 0.25\sigma^2$

Collaborative Beamforming: Theory (3/5)

Variations on a theme

- Remote source coding

$$S \rightsquigarrow X \rightarrow \boxed{\text{Enc}} \xrightarrow{\quad R \quad} \boxed{\text{Dec}} \longrightarrow \hat{S}$$

Collaborative Beamforming: Theory (3/5)

Variations on a theme

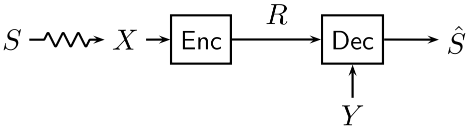
- Source coding with side information at the decoder

$$
\begin{tikzcd}
S \arrow[r] & \boxed{\text{Enc}} \arrow[r, "R"] & \boxed{\text{Dec}} \arrow[r] & \hat{S} \\
 & & Y \arrow[u] &
\end{tikzcd}
$$

Collaborative Beamforming: Theory (3/5)

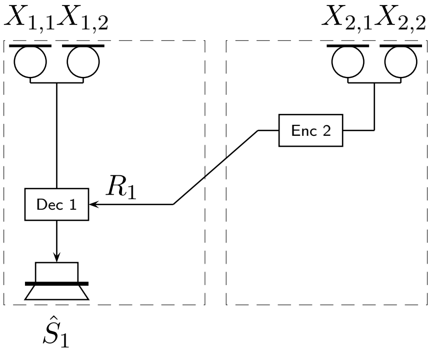
Variations on a theme

- Remote source coding with side information at the decoder



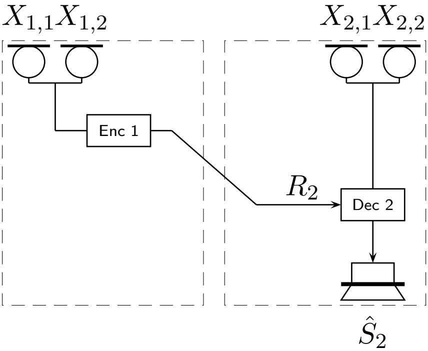
Collaborative Beamforming: Theory (4/5)

What about collaborating hearing aids? Local view



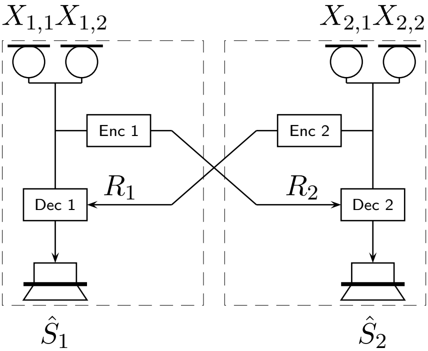
Collaborative Beamforming: Theory (4/5)

What about collaborating hearing aids? Local view



Collaborative Beamforming: Theory (4/5)

What about collaborating hearing aids? Global view



Collaborative Beamforming: Theory (5/5)

Results:

- Mean-squared optimal gain-rate tradeoffs

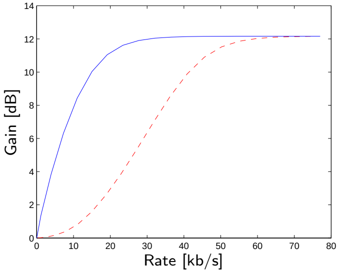


Figure: Example of gain-rate tradeoffs (two classes of coding strategies).

- Rate allocation across frequency bands
- Rate allocation between the hearing aids

Collaborative Beamforming: Practice (1/3)

From theory to practice: what do we throw away?

- Unbounded delay, unbounded complexity
- Mean-squared distortion

Collaborative Beamforming: Practice (2/3)

From theory to practice: what do we keep?

- Strong correlation between recorded signals
  - Efficiently used for estimation/coding
  - Beneficial even if signals not accessible centrally!!
- Modular approach of the optimal mean-squared solution
- Rate allocation across frequencies

Collaborative Beamforming: Practice (3/3)

Ongoing research

- Audio signal exchange between hearing aids
    - Efficient coding based on binaural cues
    - Perceptual relevance
    - Interactive communication
    - Dynamic coding scheme
- Collaborative scene analysis
- Collaborative beamforming

Conclusions

- Collaborative beamforming: theory
  - Strong assumptions to allow analytical derivations
  - Coding insights
- Collaborative beamforming: practice
  - Insights provided by theory can be used in practice
  - Perception is the driving force

Conclusions

- Collaborative beamforming: theory
  - Strong assumptions to allow analytical derivations
  - Coding insights
- Collaborative beamforming: practice
  - Insights provided by theory can be used in practice
  - Perception is the driving force

Thanks for your attention!!